Laser addressing of individual ions in a linear ion trap

H. C. Nägerl, D. Leibfried, H. Rohde, G. Thalhammer, J. Eschner, F. Schmidt-Kaler, and R. Blatt
Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, A-6020 Innsbruck, Austria
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Single ions in a linear string have been addressed with a tightly focused laser beam and an acousto-optic deflector. The excitation into a long-lived metastable level is detected with a quantum jump technique. Single-quantum bit operations for quantum information processing with trapped ions are shown to be feasible. [S1050-2947(99)01507-3]

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The physics of storage and processing of quantum information has been of rapidly growing interest during the last years. Information processing at the quantum level might have important future applications relevant to quantum computation (QC), quantum cryptography, precision spectroscopy, and the study of decoherence [1–4]. A large number of theoretical proposals on QC are based on a scheme where two-level quantum systems carry quantum information. Manipulation of single quantum bits (qubits) and interaction between qubits is mediated by laser [5,6] or radio frequency [7] radiation. Any arbitrary quantum logical process can be realized with single-qubit and two-qubit operations [8]. For experiments that are aimed to implement quantum information processing several requirements have to be fulfilled: First, the qubits have to be well decoupled from the environment to protect them against decoherence, i.e., loss of the quantum-mechanical information. It is also necessary to manipulate qubits individually to control their quantum state with so-called single qubit rotations. Furthermore, in order to implement logical gates between qubits, some well-controlled interaction between them is employed to generate entanglement. Finally, at the end of an information processing run, which in general may consist of many single- and two-bit operations, the quantum state of the qubits must be determined (i.e., read out) with ideally 100% efficiency to obtain the final result of the QC process.

Only very few existing physical systems meet all these requirements simultaneously. Cirac and Zoller were the first to propose the use of trapped ions for QC [9]. The quantum information is encoded into long-lived internal states of the ions, and the conditional dynamics (i.e., controlled-NOT operations) between qubits are implemented via laser excitation involving the electronic state of two individually addressed ions and the common quantized vibrational modes of the ion string in the trap. In order to generate arbitrary entangled states of many ions or, equivalently, to implement any quantum information process, we emphasize that all proposed schemes strictly require individual manipulations of a single qubit.

In a series of experiments on trapped $^9Be^+$ ions it has been shown recently that most of the above requirements for a QC process are indeed met by trapped ions, using highly advanced techniques of ion trapping, laser cooling, and laser manipulation of the trapped ions [10]. However, individual addressing, one of the indispensable requirements for QC, does not belong to the tools already developed in the framework of high-precision spectroscopy and optical cooling neither for single-trapped ions nor for neutral atoms. Very recently, for the case of two ions, a special addressing technique has been demonstrated. This experiment uses the reduction of excitation strength for ions that are shifted from the center of a three-dimensional Paul trap with an additionally applied dc potential. Their micromotion in the trapping potential differs, which in turn causes a difference in Rabi frequencies, even if both ions are not spatially resolved by an addressing laser beam. Bell states have been generated using this technique [11]. This experimentally used addressing scheme, however, cannot be readily scaled up to more than two ions.

In this contribution we describe the first individual addressing of single ions in a linear string with a laser beam. Our scheme combines advantages such as fast switching between different ions, low addressing errors, and easy scalability to strings of up to 10 ions. The experimental apparatus is shown in Fig. 1 and has been described in more detail in [12]: Strings of $^{40}Ca^+$ ions are stored in a linear Paul trap. The trap consists of four parallel steel rods at a distance of 2 mm, diagonally connected to generate the quadrupole rf field for radial confinement. The rf field at $\Omega/2\pi = 18$ MHz yields a radial trapping quasipotential with secular frequencies of $\omega_r = 1.4$ MHz. Two dc ring electrodes of 4-mm diameter and 10-mm spacing serve as the axial endcaps for longitudinal confinement. dc voltages of typically 150 V on the ring electrodes result in a harmonic trapping potential at an axial frequency of $\omega_z = 125$ kHz. Calcium ions produced from an atomic beam by electron impact ionization, are trapped and laser cooled. For Doppler cooling we use the dipole-allowed $S_{1/2}$-$P_{1/2}$ transition at 397 nm (for a level scheme, see inset in Fig. 1), and we reach a temperature of roughly 5 mK. Fluorescent light of the ions at 397 nm is collected, through an optical viewport, using a Nikon lens (MNH-23150-ED-Plan-1,5x) at a working distance of 65 mm. The fluorescing ion string is imaged onto an intensified CCD camera with 20-fold magnification. We observe linear ion strings of up to 15 ions, with distances between 20 μm and 7 μm (2 and 15 ions) [12]. See Fig. 2(a) for an image of 3 ions with 19-μm distance between them. An optical resolution of 4 μm for the detection of fluorescent light at 397 nm has been measured [12]. For the realization of a two-level system to implement the qubits, the $S_{1/2}$ ground state and the $D_{5/2}$

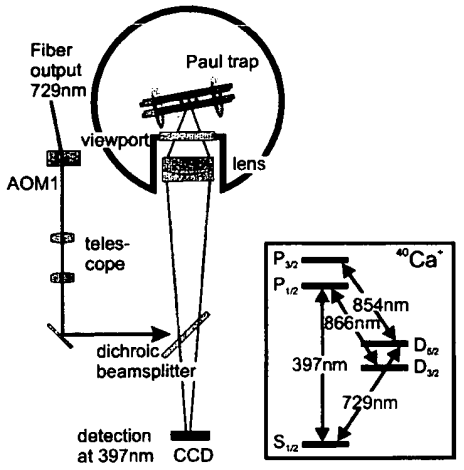

FIG. 1. Scheme of the experimental setup to address single ions in the string. Laser light at 729 nm from an optical fiber is superimposed with the fluorescence at 397 nm on a dichroic beam splitter. Thus, the laser is focused by the objective lens onto the ion string. A two-lens telescope transforms the fiber output for optimum focusing. The AOM1 can be used to shift the direction of the laser beam to address different ions in the string. Inset: relevant energy levels of $^{40}Ca^+$ and the corresponding transition wavelengths. Both D levels are metastable with a lifetime of 1 s.

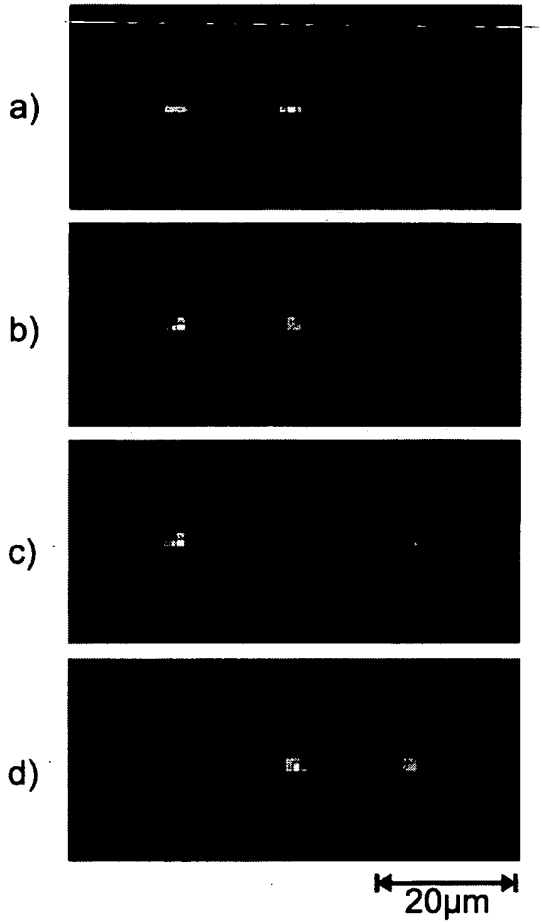

FIG. 2. (a) Fluorescence at 397 nm of three ions imaged onto the CCD camera. The distance between ions is 19.12(0.02) μm [$\omega_z = 125(0.2)$ kHz] and the spatial resolution is near 4 μm. The exposure time is 1 s. (b)–(d) Different ions in the string are addressed with focused laser light at 729 nm and transferred into the nonfluorescing $D_{5/2}$ state.

metastable state ($1s$ lifetime) are used. Coherent manipulation of the qubits on the $S_{1/2}$-$D_{5/2}$ quadrupole transition at 729 nm is achieved with a Ti:sapphire laser that has been stabilized to better than 1-kHz bandwidth. Details of the precision spectroscopy on the $S_{1/2}$-$D_{5/2}$ transition in cold Ca^+ ions will be published elsewhere [13].

Taking advantage of the high optical resolution of the Nikon lens, we use the same optical path also for individual addressing (see Fig. 1). The ingoing laser beam at 729 nm is separated from the outgoing uv fluorescence with a dichroic mirror. An optical fiber (single mode, polarization maintaining) between laser and trap setup provides stable alignment, and a telescope is used to adjust the $\lambda = 729$-nm beam parameters for optimum focusing. Between fiber exit and telescope, an acousto-optical modulator is used to shift the direction of the addressing beam and thus to allow focusing onto the different ions. The ion string is illuminated by the addressing laser under an angle $\alpha = 67.5$ degree to the trap axis in order to allow qubit excitation together with excitation of vibrational modes at frequency ω_z. With the mass m of the ion and the wave-vector k of the laser we calculate a Lamb-Dicke parameter $\eta = \sqrt{\hbar k^2 \cos^2(\alpha)/2m\omega_z} = 0.17$ for the center-of-mass motion.

We have experimentally demonstrated two ways of addressing single ions in the string: First, we used the tightly focused laser beam at a fixed position and shifted the ion string by ramping the voltages of the trap endcaps. Secondly, we fixed the ion string position and moved the laser beam over the string (see Fig. 1). The first addressing method was demonstrated with a string of three ions and the laser beam at 729 nm focused onto a fixed spot. We shifted the ion string position by slight variation (less than 1%) of the endcap ring electrode voltages. The variation of the ion string position was monitored on the CCD camera. The optical excitation sequence consists of three parts: The excitation period with light at 729 nm (0.5 ms) is followed by a detection period with the laser at 397 nm and 866 nm on (2 ms), where we registered quantum jumps to the metastable $D_{5/2}$ level. The sequence is closed by a cooling and repumping period with the lasers at 397 nm, 866 nm, and 854 nm on (2 ms). During the excitation period, we use a weak beam at 397 nm to spectrally broaden the narrow $S_{1/2}$-$D_{5/2}$ transition (see inset of Fig. 1 for the $^{40}Ca^+$ level scheme). This excitation sequence is repeated 100 times, thus yielding a value for the quantum jump probability. The average of 15 such measurements is plotted versus the center position of the ion string (see Fig. 3). From a fitted Gaussian function $A_0 + \Sigma A_i \exp\{-2[(x - x_i^0)/w_i]^2\}$ with height A_i, position x_i^0, and width w_i corresponding to the three peaks in the signal and background A_0, we obtain a spatial resolution of addressing of $w = 5.6(0.2)$ μm. This width of the Gaussian is mostly due to the optical properties of the addressing channel, since the Ca^+ ion wave packet has a calculated width of $\sqrt{\delta x^2} = 1.6$ μm at 5 mK. For exact calibration of the CCD pixel

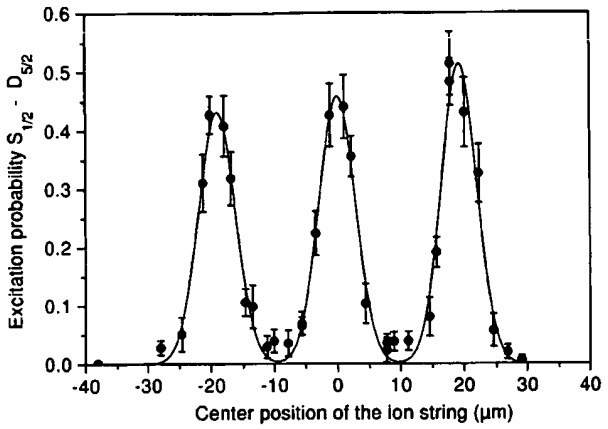

FIG. 3. Quantum jump rate from the $S_{1/2}$ to the $D_{5/2}$ state induced by a tightly focused laser beam at 729 nm. The ion string position is varied while the laser waist remains fixed. Individual ions are resolved by the addressing beam with a Gaussian width of $w=5.6(0.2)$ μm. See Fig. 2 for CCD images of the string that were taken simultaneously. The error bars indicate the one sigma deviations from 15 measurements.

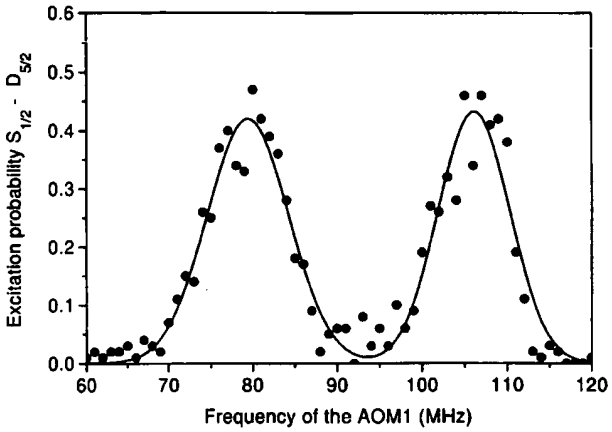

FIG. 4. Quantum jump rate from the $S_{1/2}$ to the $D_{5/2}$ state. Here the ion string position is fixed while the laser waist position is varied over two of the three ions in the string. The Gaussian fit yields a width of $w=6.6(0.4)$ μm (left) and $w=5.7(0.4)$ μm (right). All parameters of the ion trap and the distance between ions are identical to those in Figs. 2 and 3. The errors of the quantum jump rates in this measurement are similar to those in Fig. 3.

size we used a resonant excitation of the center-of-mass mode of the ion string [14]. From the measured frequency of 125(0.2) kHz we obtain a distance of 19.12(0.02) μm [15]. Thus, we can calibrate exactly the pixel size of the recorded CCD images to 1.12 μm per pixel. In Figs. 2(b)–2(d) we show CCD images of the addressed string, with different ions transferred to the nonfluorescing $D_{5/2}$ state. Assuming a Gaussian intensity distribution, the intensity of the addressing beam at the position of the next ion 19 μm away is completely negligible. Spatial filtering of the optical mode of the fiber might further improve the resolution. However, we suspect the optical properties of the vacuum viewport to distort slightly the focused beam.

After having shown sufficiently good spatial resolution for individual addressing, we implemented a scheme that would be directly applicable to a future quantum information process. Shifting the ion string does not allow sufficiently fast switching for longer ion strings, since a fast, nonadiabatic shift of position would presumably cause heating [4]. For fast addressing, the laser beam is shifted by an acousto-optical modulator (AOM1) and thus focused on different ions. The associated change in frequency is compensated by a second double-pass acousto-optical modulator (AOM2) in front of the fiber. To demonstrate this method, we have taken data on a string of three ions with parameters similar to those of the string shown in Fig. 2. Due to the limited 30-MHz bandwidth of the currently used AOM1, the laser beam could be displaced only over two of the three ions. The excitation probability is plotted in Fig. 4 as a function of the AOM1 drive frequency. The Gaussian fit to the data yields slighly different widths for the two ions, 6.6(0.4) μm (left) and 5.7(0.4) μm (right), which is due to their different levels of saturation. The smaller width, at lower saturation, can be taken as a conservative estimate for the spatial resolution in this case. With the above calibration, we have a shift of 0.712 μm/MHz of the laser beam at the ion string position, with a maximum shift of 40 μm for our optical setup.

We plan to increase the longitudinal trap frequency in future experiments such that the ion strings will have smaller spacings. Our measured addressing resolution will allow us to increase the longitudinal trap frequency to 500 kHz with interion distances of 8.9 μm and 7.6 μm (for two and three ions, respectively). For an inter-ion distance of only 7.6 μm, the addressing error would be 2.5%. Higher longitudinal trap frequencies will reduce the thermal phonon number after Doppler cooling and thus faciliate ground-state cooling. Secondly, since the vibrational sidebands have to be spectrally resolved by the addressing laser, the inverse of the trap frequency sets a lower limit to pulse length used in logic operations.

In conclusion, we have performed an experiment to address single ions in a string with a spatial resolution of 5.6 μm. This is one of the fundamental ingredients of theoretical proposals that utilize trapped ions for quantum information processing. The ions are excited by a focused laser beam at 729 nm on the quadrupole transition between the $S_{1/2}$ ground state and the metastable $D_{5/2}$ level. Fast addressing of the ions is achieved with an acousto-optical modulator. This technique offers advantageous features for quantum information processing such as scalability to many ions, low addressing errors, and fast switching between the qubits. The obtained resolution permits one to work with higher longitudinal trap frequencies of 500 kHz–1 MHz with inter-ion distances of 8–6 μm. Switching between the ions within μs is feasible with an acousto-optical modulator and will allow roughly ten operations within the coherence time of 500 μs that we measured [13]. The addressing technique will further allow us to investigate selectively the temperature and heating rate [4] for different vibrational modes, and for ions at different locations in the ion string. It might further be used for spatially resolved precision frequency measurements on ions at different locations in a linear string. The specification

of optical clock transitions will use the measurement of micromotion [16] for ions at different positions in the string to determine and eventually correct the corresponding frequency shifts. This should be as well interesting for the investigation of time standards based on trapped ions [17].

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